

PREPARED FOR SUBMISSION TO JHEP

# Probing Sterile Neutrino Parameters with Double Chooz, Daya Bay and RENO

---

Kalpana Bora,<sup>a</sup> Debajyoti Dutta<sup>a</sup> and Pomita Ghoshal<sup>b</sup>

<sup>a</sup>*Physics Department  
Gauhati University,  
Assam, India*

<sup>b</sup>*Physical Research Laboratory,  
Navrangpura, Ahmedabad, India*

*E-mail:* [kalpana.bora@gmail.com](mailto:kalpana.bora@gmail.com), [debajyotidutta1985@gmail.com](mailto:debajyotidutta1985@gmail.com),  
[pomita.ghoshal@gmail.com](mailto:pomita.ghoshal@gmail.com)

**ABSTRACT:** In this work, we present a realistic analysis of the potential of the present-day reactor experiments Double Chooz, Daya Bay and RENO for probing the existence of sterile neutrinos. We present exclusion regions for sterile oscillation parameters for each of these experiments, using simulations with realistic estimates of systematic errors and detector resolutions, and compare the sterile parameter sensitivity regions we obtain with the existing bounds from other reactor experiments. We find that these experimental setups give significant bounds on the parameter  $\Theta_{ee}$  especially in the low sterile oscillation region  $0.01 < \Delta m_{41}^2 < 0.05 \text{ eV}^2$ . These bounds can add to our understanding of the sterile neutrino sector since there is still a tension in the allowed regions from different experiments for sterile parameters.

**KEYWORDS:** Sterile Neutrino, Exclusion Plot

ARXIV EPRINT: [1206.2172](https://arxiv.org/abs/1206.2172)

---

## Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
<b>2</b>	<b>Theory of Neutrino Oscillations with Sterile Neutrinos</b>	<b>2</b>
<b>3</b>	<b>Details of the experiments</b>	<b>4</b>
3.1	Double Chooz experiment	4
3.2	Daya Bay	4
3.3	RENO	5
<b>4</b>	<b>Details of old experiments</b>	<b>6</b>
<b>5</b>	<b>Results</b>	<b>6</b>
<b>6</b>	<b>Conclusions</b>	<b>9</b>

---

## 1 Introduction

For a long time, it was taken as an accepted fact that there are three families of fermions, and hence three neutrino flavours. But experiments like LSND [1] and now MiniBooNE [2] have indicated the presence of a fourth type of neutrino - the sterile neutrino. Sterile neutrinos do not carry Standard Model gauge quantum numbers, so they do not take part in Standard Model gauge interactions, but they can mix with the other 3 active neutrinos. The LSND result provided evidence for  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  oscillations from  $\mu^+$  decay-at-rest (DAR), and the same oscillation channel was studied in the MiniBooNE experiment. Similar results are also indicated by  $\bar{\nu}_e$  and  $\nu_e$  disappearance channels, by the reactor anomaly [3] and Gallium anomaly [4, 5], and from cosmology [6–10]. These results suggest that the deficit of observed neutrino fluxes in the respective channels ( $\nu_e$  or  $\bar{\nu}_e$ ) may be an indication of the existence of a fourth type of neutrino. We know that the peak energy of  $\bar{\nu}_e$  produced during beta decay in reactors is  $\sim 3.5$  MeV. If the typical baseline of a neutrino oscillation experiment is  $\sim 1$  m, then the order of  $\Delta m^2$  which could be detected is  $\sim \frac{1m}{1MeV} \sim 1$  eV<sup>2</sup>. This is the relevant scale for the oscillation of active neutrinos to sterile neutrinos.

The latest global fits of sterile neutrino parameters were presented in [11, 12]. In [11], a fit of all present and past experiments giving bounds on the sterile parameters is performed in a (3+1) scenario (i.e., 3 active and 1 sterile neutrino flavors). The short baseline neutrino oscillation results from KARMEN [13, 14], LSND [15],  $\nu_e + {}^{12}\text{C} \rightarrow {}^{12}\text{N}_{g.s.} + e^-$ , as suggested in [16] have also been included. Their best fit values at 95 % CL, including MiniBooNE  $\nu_e$  and  $\bar{\nu}_e$  data, are  $\sin^2 2\Theta_{ee} = 0.1$  and  $\Delta m_{41}^2 = 0.9$  eV<sup>2</sup>. Earlier, such global analyses on sterile neutrino parameters in (3+1) or (3+2) scenarios have been presented in [17–23].

A significant amount of work is already available in the literature regarding the search for sterile neutrinos in reactor and atmospheric neutrino oscillation experiments. Recently the possibility of using atmospheric neutrinos as a probe of  $eV^2$ -scale active-sterile oscillations was explored in [24], where bounds on  $\sin^2 2\Theta_{\mu\mu}$  and  $\Delta m_{41}^2$  were presented. The implication of sterile neutrinos on measurements of  $\theta_{13}$  in a  $(3+2)$  scenario in the Double Chooz [25] reactor experiment was studied in [26]. The impact of light sterile neutrinos on  $\theta_{13}$  measurements in Double Chooz and Daya Bay [27] was studied in [28] in a  $(3+1)$  scenario. A study of the effect of sterile neutrinos on  $\theta_{23}$  and  $\theta_{13}$  measurements in MINOS, T2K and Double Chooz was performed in [29]. Similar studies for Daya Bay were carried out in [30]. A search for sterile neutrinos using MINOS was done in [31]. A constraint on the mixing angle  $\theta_{14}$  from a combination of Solar and KamLAND data was given in [32, 33]. An analysis of the results of Double Chooz, Daya Bay and RENO to simultaneously fit  $\theta_{13}$  and the reactor neutrino anomaly was recently performed in [34].

In this work, we present exclusion regions in the sterile neutrino parameter space  $\sin^2 2\Theta_{ee} - \Delta m_{41}^2$  for the three current reactor experiments, namely Double Chooz, RENO [35] and Daya Bay. A similar study was performed in [28] for Double Chooz and Daya Bay, where a more approximate analysis in the  $\sin^2 2\Theta_{ee} - \Delta m_{41}^2$  plane was done assuming an overall systematic error and neglecting detector resolution. In our present work, we have used simulations with reduced values of errors, as quoted in the technical reports of the individual reactor experiments, where the cancellation of correlated reactor-related errors by using both near and far detectors has been taken into account. Also, we have considered realistic detector resolutions, which play an important part in the sensitivity analysis. The allowed regions in  $\sin^2 2\Theta_{ee} - \Delta m_{41}^2$  plane presented in this work are relevant in view of the fact that there is still significant tension in the existing data between appearance and disappearance experiments. Although an exclusion region is quoted in the present global best-fit scenario [11], we have tried to survey critically the region which would be accessible by this specific set of new reactor experiments, to see what it adds to existing information. We also compare our results with those of older reactor experiments like BUGEY [36], GOSGEN [37] and Krasnoyarsk [38].

The paper has been organized as follows. In Section 2, we briefly present the theory of neutrino oscillations with sterile neutrinos. In Section 3, we describe the details of the three reactor experiments we study, as listed in the technical reports of each experiment. We also give details of systematic errors and detector resolutions used in our analysis. In Section 4, we present our results, and conclude with a discussion of the results in Section 5.

## 2 Theory of Neutrino Oscillations with Sterile Neutrinos

We know that neutrino mass and flavor eigenstates can be related by the relation

$$\nu_\alpha = U_{\alpha i} \nu_i, \quad (2.1)$$

where  $U$  is a unitary matrix. In matrix form, this mixing between flavor eigenstates  $\nu_\alpha$  ( $\alpha = e, \mu, \tau, s$ ; where  $s$  stands for sterile neutrino) and mass eigenstates  $\nu_j$  ( $j = 1, 2, 3, 4$ ) in four

neutrino scenario can be represented as

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix} \quad (2.2)$$

This unitary matrix can be parametrized [39] as

$$U = R_{34}(\theta_{34}, 0) R_{24}(\theta_{24}, 0) R_{23}(\theta_{23}, \delta_3) R_{14}(\theta_{14}, 0) R_{13}(\theta_{13}, \delta_2) R_{12}(\theta_{12}, \delta_1) \quad (2.3)$$

where  $R_{ij}(\theta_{ij}, \delta_k)$  is the complex rotation matrix in the  $i$ - $j$  plane and the elements are given by

$$[R_{ij}]_{pq} = \begin{cases} \cos \theta & p = q = i & \text{or} & p = q = j \\ 1 & p = q \neq i & \text{and} & p = q \neq j \\ \sin \theta e^{-i\delta} & p = i & \text{and} & q = j \\ -\sin \theta e^{i\delta} & p = j & \text{and} & q = i \\ 0 & \text{otherwise} \end{cases} \quad (2.4)$$

Here,  $\theta_{ij}$  is the angle of rotation in  $i$ - $j$  plane [17, 39]. If we assume  $\theta_{14}, \theta_{24}, \theta_{34} = 0$  then the above mixing matrix reduces to the standard Pontecorvo-Maki-Nakagawa-Sakata (PMNS) [40–42] form. Here we consider the (3+1) scenario, which is an extension of the three-neutrino scenario with the addition of one massive sterile neutrino. Solar and atmospheric neutrino analyses strongly discourage the (2+2) scenario due to the absence of sterile signals in the atmospheric parameters [43]. The (3+2) scenario is favoured by the tension between appearance and disappearance experiments in the (3+1) case, but disfavoured by cosmology.

The three new reactor experiments we have considered have two detectors, one at the far site and the other at the near site. In these experiments, the electron antineutrino disappearance probability is measured through electron antineutrino events. The far detector is placed at sufficient distance from the reactor site (compared to the near one) so as to maximise the disappearance of the electron anti-neutrino. Such a two-detector set up has a great advantage over a single detector, as it can cancel or reduce the systematic uncertainties.

In the presence of a sterile neutrino, the standard 3-flavor neutrino oscillation picture changes, and hence the survival probability must be modified due to the effect of (3+1) mixing. The baselines relevant to these experiments are of the order of a few hundred metres, and hence the oscillation would show signatures at the atmospheric scale as well as possible sterile-scale effects. The electron neutrino survival probability expression relevant for our analysis is [28] -

$$P_{ee} = 1 - \cos^4 \theta_{14} \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{13}^2 L}{4E} \right) - \sin^2 2\theta_{14} \sin^2 \left( \frac{\Delta m_{14}^2 L}{4E} \right), \quad (2.5)$$

Reactor No	Near detector(km)	Far detector(km)
1	0.47	1.12
2	0.35	1.00

**Table 1.** Core to detector distances in Double Chooz

where  $L$  is the baseline and  $E$  is the neutrino energy. Here,  $P_{ee}$  is seen to be a function of two mass-squared differences ( $\Delta m_{14}^2$  and  $\Delta m_{13}^2$ ) and two mixing angles  $\theta_{13}$  and  $\theta_{14}$ . When  $\theta_{14} \rightarrow 0$ , we recover the standard three-flavour probability expression in which the solar mass scale is neglected.

### 3 Details of the experiments

In this section, we present some technical details of the experiments for the sake of completeness, collected from [25, 27, 35].

#### 3.1 Double Chooz experiment

The Double Chooz reactor experiment [25, 35] is designed to detect  $\bar{\nu}_e$  through the inverse  $\beta$  reaction-

$$\bar{\nu}_e + p \rightarrow e^+ + n \quad (3.1)$$

The anti-neutrino flux coming from the two nuclear cores of the Chooz power plant results from the  $\beta$  decay of the fission products of four main isotopes-  $^{235}\text{U}$ ,  $^{239}\text{Pu}$ ,  $^{241}\text{Pu}$  and  $^{238}\text{U}$ . The Double Chooz far detector is cylindrical in shape, having a radius of 115 cm and a height of 246 cm, and hence a volume of  $10.3 \text{ m}^3$ . Both near and far detectors are identical inside the PMT support structure and the mass of each is about 10.16 tons. The reactor site contains two reactors, each producing a thermal power of 4.27 GW. The near detector is situated roughly at a distance of 410 m from the reactor site, while the far one is at a distance of 1067 m. The reactor core-to-detector distances are tabulated in table 1.

In our analysis, we have considered an exposure time of three years with a 12% detector resolution. The  $\chi^2$  function we have used is taken from the collaboration report.

#### 3.2 Daya Bay

The Daya Bay neutrino experiment [27] works with reactor generated electron antineutrinos and uses a gadolinium (Gd) loaded liquid scintillator detector. It has two pair of reactors at Daya Bay and Ling Ao I, which generate 11.6 GW of power. One more reactor site at Ling Ao II is under construction. Daya Bay consists of three underground experimental halls, one far and two near, linked by horizontal tunnels. Eight identical cylindrical detectors are employed to measure the neutrino flux. The mass of each detector is about 20 tons. Four of these eight detectors are at the far zone while two detectors are kept in each near zone. The distance of the detectors from the reactor cores at the Daya Bay site is 363 m while this distance at the Ling Ao site is 481 m. The far detectors are at 1985 m and 1615 m

Reactor No	Near detector(km)	Far detector(km)
1	0.70	1.52
2	0.48	1.43
3	0.32	1.39
4	0.32	1.39
5	0.48	1.43
6	0.70	1.52

**Table 2.** Core to detector distances in RENO

Name of Exp	Double Chooz	Daya Bay	RENO
Location	France	China	Korea
No of Reactor cores	2	4	6
Total Power( $\text{GW}_{th}$ )	8.7	11.6	16.4
Baselines- near/Far(m)	410/1067	363(481)/1985(1615)	292/1380
Target mass(tons)	10/10	$40 \times 2/10$	16.1/16.1
No of Detectors	2	2	2
Exposure(years)	3	3	3
Resolution(%)	12	12	12

**Table 3.** Details of the three reactor experiments

respectively from the Daya Bay and Ling Ao reactor sites. We have used an exposure time of 3 years, with 12% resolution.

### 3.3 RENO

The RENO experiment [35] is designed to search for reactor antineutrino disappearance using two identical detectors. The set-up consists of a near detector roughly 292 m away from the reactor array center, while the far detector is about 1.4 km away from the reactor array center. This design of identical detectors at the two sites helps in reducing systematic errors. Each detector contains 16 tons of liquid scintillator which is doped with gadolinium. There are six reactor cores in RENO, for which the core to detector distances are listed in Table 2.

The average total thermal power output of the six reactor cores is  $16.4 \text{ GW}_{th}$ , with each reactor core generating about equal power. The energy of the antineutrinos in these experiments is in the range of 1 to 8 MeV. The resolution is 12%.

We present the particulars of the three reactor experiments in Table 3.

The systematic errors associated with each experimental set-up are listed in Table 4.<sup>1</sup>

---

<sup>1</sup>Since we did not find specific values of the scaling and overall normalization errors of the Daya Bay experiment in the literature, we have assumed values similar to Double Chooz.

Name of Exp	Double Chooz	Daya Bay	RENO
Reactor correlated error(%)	2.0	2.0	2.0
Detector normalisation error(%)	0.6	0.5	0.5
Scaling or calibration error(%)	0.5	0.5	0.1
Overall normalization error(%)	2.5	2.5	2.0
Isotopic abundance error(%)	2.0	2.0	2.0

**Table 4.** Systematic errors associated with the three experiments

## 4 Details of old experiments

The details of the three old reactor experiments (BUGEY [36], Gosgen [37] and Krasnoyarsk [38]) with which we compare our exclusion regions for sterile parameters are tabulated in Table 5.

## 5 Results

We have generated the 90% c.l. exclusion plots for sterile oscillations for all the three current experiments and compared the results with the old reactor experiments Bugey, Gosgen and Krasnoyarsk. The right side of each contour shows the no-oscillation region while the region left to the contours is the possible oscillation region. The results are found to be very sensitive to the values of systematic errors. In our calculations, we have used GLoBES [44–48] for simulating the experiments. The details of the statistical analysis are as follows: the total no of bins used in all three experiments are 62 and the width of the energy window is 1.8-8 MeV. The resolution used is 12 %. The uncertainty associated with the shape of neutrino energy spectrum for all the three experiments is 2 %. In our calculation we have used the  $\chi^2$  function as defined in the GLoBES manual and used in standard GLoBES sensitivity analysis:

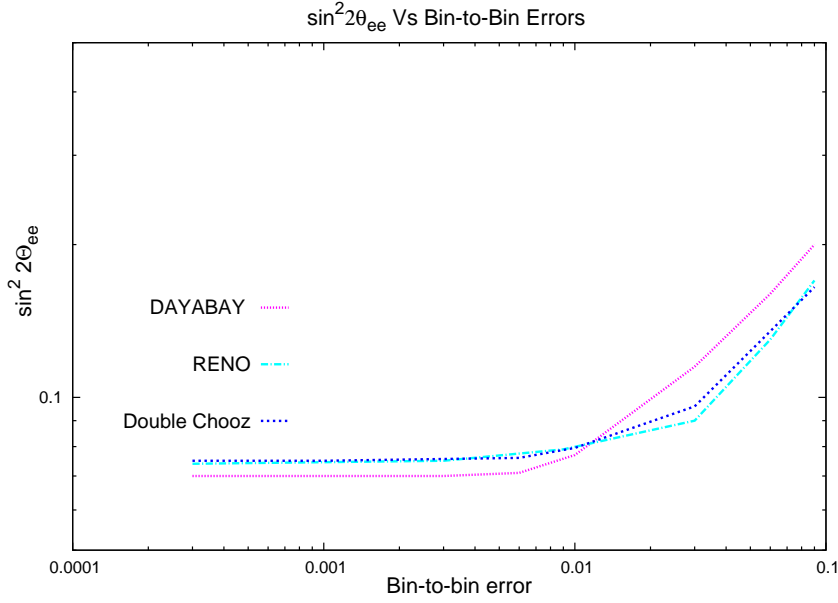
$$\chi^2 = \sum_{i=1}^{\#bins} \sum_{d=N,F} \frac{(O_{d,i} - (1 + a_R + a_d)T_{d,i})^2}{O_{d,i}} + \frac{a_R^2}{\sigma_R^2} + \frac{a_N^2}{\sigma_N^2} + \frac{a_F^2}{\sigma_F^2} \quad (5.1)$$

where  $O_{N,i}, O_{F,i}$  are the event rates for the  $i^{th}$  bin in the near and far detectors, calculated for true values of oscillation parameters;  $T_{d,i}$  are the expected event rates for the  $i^{th}$  bin in the near and far detector for the test parameter values;  $a_R, a_F, a_N$  are the uncertainties associated with the reactor flux and detector mass; and  $\sigma_R, \sigma_F, \sigma_N$  are the respective associated standard deviations.

Fig.1 shows the variation of the average bound on  $\sin^2 2\theta_{ee}$  from each of the three experiments Double Chooz, Daya Bay and RENO as a function of the bin-to-bin systematic

Name of Exp	Bugey	Gosgen	Krasnoyarsk
No of Reactor cores	4	1	3
Total Power( $\text{GW}_{th}$ )	2.8	2.8	2.8
Baselines(m)	15,40,95	37.9,45.9,64.7	57,57.6,231.4
Target mass( $\approx$ tons)	1.67	0.32	0.4
No of Detectors	1	1	1
Exposure( $\approx$ years)	0.2	0.39,0.56,0.98	0.06
Resolution(%)	6	-	-

**Table 5.** Details of old reactor experiments



**Figure 1.** Dependence of the average  $\sin^2 2\theta_{ee}$  bound on the correlated bin-to-bin error for Double Chooz, Daya Bay and RENO.

error for a constant overall normalisation. We depict the behavior with respect to the correlated bin-to-bin error since this is found to have the most significant effect on parameter sensitivities. The figure shows that the dependence of the sensitivity in the case of Daya Bay is slightly steeper, even for low values of the bin-to-bin systematics, than for the other two experiments.

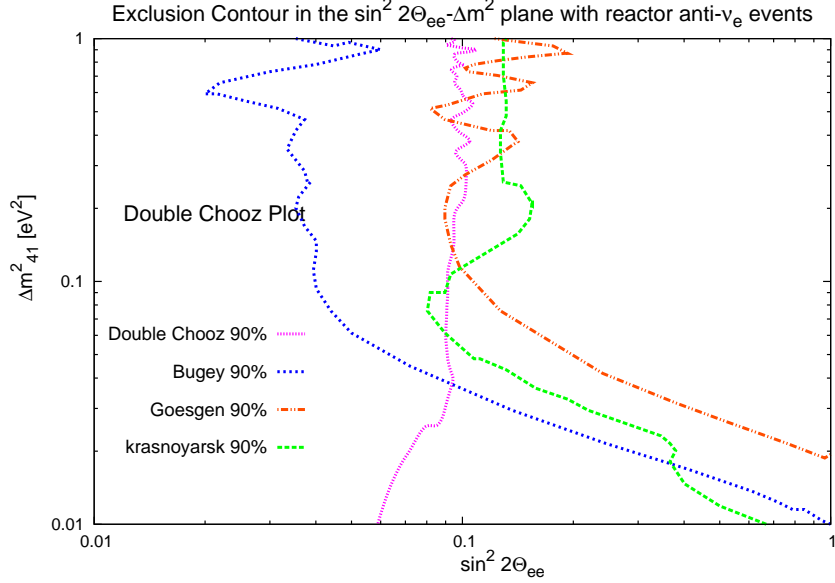
In our further analysis, we have used a reduced set of systematic errors as listed in Table 6, taking into account the partial cancellation of errors due to the presence of both near and far detectors, as documented in the experiment literature.

We have included the changed flux normalizations given by the reactor flux anomaly



Name of Exp	Double Chooz	Day Bay	RENO
Reactor correlated error(%)	0.06	0.087	0.5
Detector normalisation error(%)	0.06	0.12	0.5
Scaling or calibration error(%)	0.5	0.5	0.1
Overall normalization error(%)	0.5	0.5	0.5
Isotopic abundance error(%)	0.06	0.087	0.5

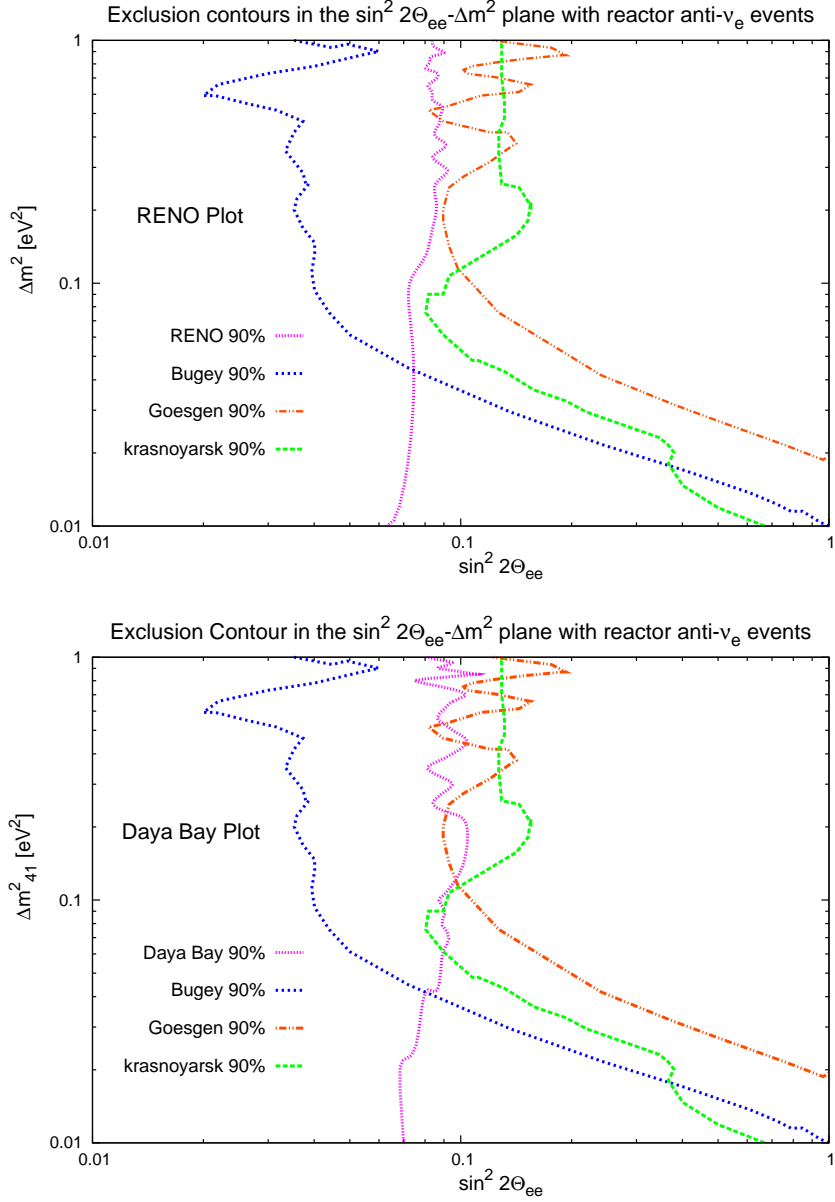
**Table 6.** Set of reduced errors used in our calculation



**Figure 2.** Comparison of Double Chooz exclusion plot with other reactor experiments at 12% resolution using modified errors.

[3] in our sensitivity analysis. We are performing a simulation and not a data analysis, and hence varying the flux normalizations has minimal effect on our results, since the relative normalizations simultaneously affect both the true and test spectra in the simulation and lead to a cancellation of their effect in the parameter sensitivity. For the same reason, leaving the flux normalization as a freely varying parameter does not have a major influence on our results, and therefore they may be taken to be indicative of the effect of spectral information only.

In Fig.2 and 3, we show the comparison of the exclusion plots for Double Chooz, RENO and daya Bay experiments with existing reactor experiments using modified errors. Our results for all the three experiments show better exclusion regions for sterile neutrino oscillation parameters than Gosgen and Krasnoyarsk in the range  $\Delta m^2_{41}=0.01$  to  $1 \text{ eV}^2$ . Our bounds are an improvement over Bugey in the range  $\Delta m^2_{41}=0.01$  to  $0.05 \text{ eV}^2$  but in the  $\Delta m^2_{41}$  region above this, Bugey gives better bounds. From these curves, we see that  $\sin^2 2\theta_{ee} > 0.1$  and  $\sin^2 2\theta_{ee} > 0.08$  is excluded for sterile oscillation in the  $\Delta m^2_{41}=0.01$



**Figure 3.** Comparison of RENO and Daya Bay exclusion plots with other reactor experiments at 12% resolution using modified errors.

to  $1eV^2$  region for Double Chooz and RENO respectively. The Daya Bay exclusion bound in the region  $\Delta m_{41}^2=0.1$  to  $1 eV^2$  is found to be nearly  $\sin^2 2\theta_{ee} > 0.07$ .

## 6 Conclusions

From the above results, we can draw the following conclusions:

- The sensitivity of reactor experiments like Double Chooz, Daya Bay and RENO to sterile oscillation parameters is significantly dependent on the systematic errors, de-

tector resolutions and uncertainties of each experiment. The dependence is especially strong on the correlated reactor-related errors and the normalization uncertainty.

- Because of the multiple detectors and baselines in each of these experimental set-ups, it is possible to have partial cancellations of the experimental errors, especially of the correlated errors, which is beneficial in giving us better parameter sensitivities.
- In an analysis with duly reduced values of errors, it is possible to obtain better bounds with these set-ups than those from many of the older reactor experiments, in spite of the fact that the relatively higher baselines in this case are less suited for a determination of oscillations in the  $\Delta m_{14}^2 = 1 \text{ eV}^2$  range. For the latter reason, we find that we obtain better bounds in the low region  $0.01 < \Delta m_{14}^2 < 0.05 \text{ eV}^2$ .

It may be noted that this region lies below the present best-fit range for sterile-scale oscillations. However, the tension between the sterile parameter bounds from different sets of experimental data like the appearance and disappearance experiments indicates that there is still significant uncertainty on the favored region. It is possible that the global fit regions may shift appreciably in the future. In view of this, these results are significant in showing that present reactor experiments like Double Chooz, Daya Bay and RENO may be able to give improved sterile oscillation bounds in specific regions of the parameter space. Such signatures may contribute in modifying the overall picture of sterile oscillation parameter sensitivity.

### Acknowledgements

We would like to thank Raj Gandhi for extensive discussions and suggestions. We thank the XI Plan Neutrino Project at HRI, Allahabad, for providing financial assistance to visit HRI, during which major parts of the work have been carried out. KB and PG would like to thank Thomas Schwetz for his useful comments and discussions. KB also thanks UGC SAP program (to Physics Department, Gauhati University) for providing financial assistance.

### References

- [1] A. Aguilar et al. (LSND), Phys. Rev. D64, (2001) 112007, arXiv:hep-ex/0104049.
- [2] A. A. Aguilar-Arevalo et al. (MiniBooNE), Phys. Rev. Lett. 105, (2010) 181801, arXiv:hep-ex/1007.1150.
- [3] G. Mention et. al., Phys. Rev. D83, (2011) 073006, arXiv:hep-ph/1101.2755.
- [4] GALLEX, P. Ansetmann et. al., Phys. Lett B342, (1995) 440.
- [5] SAGE, J. N. Abdurashitov et. al., Phys. Rev. C80, (2009) 015807, arXiv: hep-ph/0901.2200.
- [6] J. Hamann, S. Hannestad, G. G. Raffelt, I. Tamborra, and Y. Y. Wong, Phys. Rev. Lett. 105, (2010) 181301, arXiv:hep-ph/1006.5276.
- [7] E. Giusarma et al., Phys. Rev. D83, (2011) 115023 , arXiv:astro-ph/1102.4774.
- [8] J. R. Kristiansen and O. Elgaroy, arXiv:astro-ph/1104.0704.

- [9] Z. Hou, R. Keisler, L. Knox, M. Millea, and C. Reichardt, arXiv:astro-ph/1104.2333.
- [10] A. X. Gonzalez-Morales, R. Poltis, B. D. Sherwin, and L. Verde, arXiv:astro-ph/1106.5052.
- [11] C. Guinti and M. Laveder, arXiv:hep-ph/1111.1069.
- [12] C. Guinti and M. Laveder, arXiv:hep-ph/1109.4033.
- [13] KARMEN, B. E. Bodmann et. al., Phys. Lett B332, (1994) 251.
- [14] B. Armbruster et. al., Phys. Rev. C57, (1998) 3414, arXiv:hep-ex/98101007.
- [15] LSND, L. B. Auerbach et. al., Phys. Rev C64, (2001) 065501, arXiv:hep-ex/0105068.
- [16] J. Conard and M. Shaevitz, arXiv:hep-ph/1106.5552.
- [17] M. Maltoni and T. Schwetz, Phys. Rev. D76, (2007) 093005, arXiv:hep-ph/0705.0107.
- [18] J. Kopp, M. Maltoni, T. Schwetz, arXiv:hep-ph/1103.4570.
- [19] G. Karagiorgi et. al., Phys. Rev D80, (2009) 073001, arXiv:hep-ph/0906.1997.
- [20] E. Akhmedov and T. Schwetz, JHEP 1010, (2010) 115, arXiv:hep-ph/1007.4171.
- [21] C. Guinti and M. Laveder, Phys. rev D83, (2011) 053006, arXiv:hep-ph/1012.0267.
- [22] C. Guinti, arXiv:hep-ph/1106.4479.
- [23] C. Guinti and M. Laveder, arXiv:hep-ph/1107.1452.
- [24] R. Gandhi and P. Ghoshal, arXiv:hep-ph/1108.4360.
- [25] Double CHOOZ collaboration, F. Ardellier et al., hep-ex/0606025 .
- [26] A. Bandhyopadhyay and S. Choubey, arXiv: hep-ph/0707.2481.
- [27] Daya Bay proposal, arXiv:hep-ex/0701029.
- [28] A. de Gouvea and T. Wytock, arXiv:0809.5076.
- [29] B. Bhattacharya, Arun M. Thalappilil, C. E. M. Wagner , arXiv:hep-ph/1111.4225.
- [30] D. A. Dwyer et. al., arXiv:hep-ph/1109.6036.
- [31] A. B. Sousa, arXiv:hep-ph/1110.3455.
- [32] A. Palazzo, Phys. Rev. D 83, (2011) 113013, arXiv:hep-ph/1105.1705.
- [33] A. Palazzo, Phys. Rev. D 85, (2012) 077301, arXiv:hep-ph/1201.4280.
- [34] J. Evslin, H. Li, E. Ciuffoli, arXiv:hep-ph/1205.5499.
- [35] J. K. Ahn, S. R. Baek, S. Choi, arXiv:hep-ph/1003.1391.
- [36] Bugey, B. Achkar et al., Nucl. Phys. B434, (1995) 503 .
- [37] Gosgen, G. Zacek et al., Phys. Rev. D 34, (1986) 2621.
- [38] Krasnoyarsk, G. S. Vidyakin et al., Sov. Phys. JETP 71, (1990) 424.
- [39] O. Yasuda, arXiv:hep-ph/1004.2388.
- [40] B. Pontecorvo, Sov. Phys. JETP 26 (1968) 984 [Zh. Eksp. Teor. Fiz. 53 (1967) 1717].
- [41] B. Pontecorvo, Sov. Phys. JETP 6 (1957) 429 [Zh. Eksp. Teor. Fiz. 33 (1957) 549].
- [42] Z. Maki, M. Nakagawa and S. Sakata, Prog. Theor. Phys. 28, (1962) 870.
- [43] M. Maltoni, T. Schwetz, M. Tortola, and J. Valle, New J. Phys. 6, (2004) 122, arXiv:hep-ph/0405172.

- [44] P. Huber, J. Kopp, M. Lindner, M. Rolinec, and W. Winter, JHEP 05, (2006) 072, arXiv:hep-ph/0601266.
- [45] P. Huber, J. Kopp, M. Lindner, M. Rolinec, and W. Winter, arXiv:hep-ph/0701187.
- [46] P. Huber, M. Lindner, T. Schwetz and W. Winter, arXiv:hep-ph/0907.1896.
- [47] P. Huber, M. Lindner, and W. Winter, Comput. Phys. Commun. 167, (2005) 195 , arXiv:hep-ph/0407333.
- [48] GLoBES manual (2004), <http://www.mpi-hd.mpg.de/~globes>